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S. Peery and A. Minick (P&W) "Design and Development of an Advanced Expander Combustor"

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DESIGN AND DEVELOPMENT OF AN ADVANCED EXPANDER COMBUSTOR

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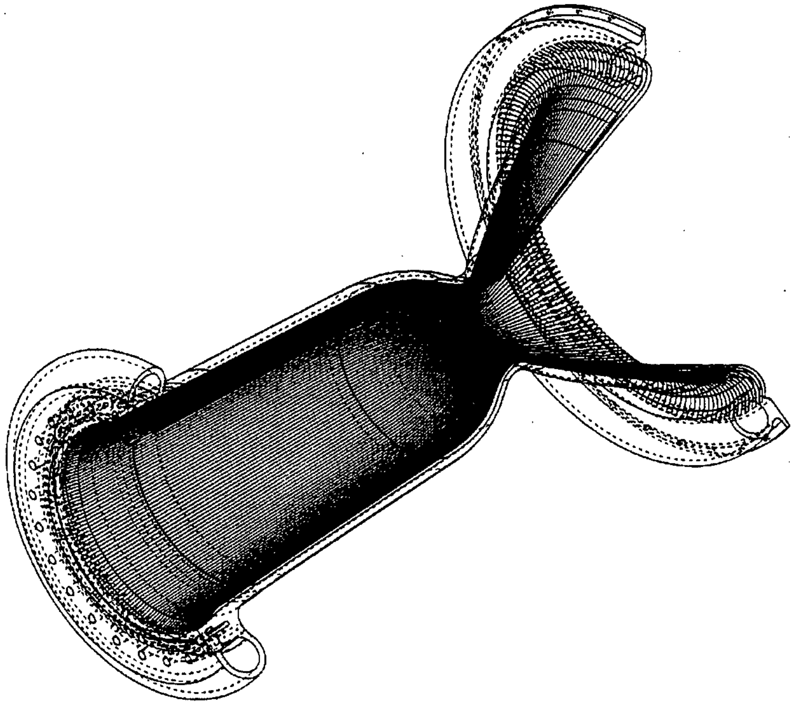
West Palm Beach, Fla.



34th AIAA/ASME/SAE/ASEE
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ABSTRACT

This paper discusses design and development of an advanced expander combustion chamber for a 50,000 pound (222.4 kN) thrust Upper Stage Expander Cycle Engine being developed by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratories (AFRL) to support the Integrated High Payoff Rocket Technology (IHPRPT) program. The Advanced Expander Combustor is designed to provide increased heat pick-up to the coolant and improved system thrust to weight, increased specific impulse, and increased reliability. These benefits will be accomplished and demonstrated through design, development, and test of this high heat flux, compact thrust chamber capable of supporting a chamber pressure of 1375 psia (97 kg/cm**2) in an expander cycle configuration.

INTRODUCTION

The Air Force, Army, Navy, and NASA have implemented a three phase, 15 year rocket propulsion technology improvement effort to "double rocket propulsion technology by the year 2010". This initiative, designated the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) established performance, reliability, and cost improvement goals for each of the three phases. These goals are to be met by advancing component technology levels through design, development, and demonstration, followed by an integrated system level demonstrator to validate performance to the IHPRPT system level goals. Pratt & Whitney Liquid Space Propulsion, under contract to the United States Air Force Research Laboratory (contract F04611-95-C-0123), is developing the Advanced Expander Combustor (AEC) combustion chamber. This combustion chamber is designed to be used with the Advanced Liquid Hydrogen (ALH) lc turbopump (Ref. AIAA 98-3681 *Design and Development of an Advanced Liquid Hydrogen Turbopump*) in the 50k LOX/Hydrogen Upper Stage Demonstrator (Ref. AIAA 98-3676 *Design and Development of a 50k LOX/Hydrogen Upper Stage Demonstrator).* This demonstrator will be test fired in late 2000 to demonstrate the IHPRPT LOX/LH2 boost/orbit transfer propulsion area phase I goals. These system level goals include; a 1% improvement in vacuum specific impulse, a 30% improvement in thrust to weight, a 15% reduction in hardware/support costs, and a 25% improvement in reliability relative to the current state-of-the-art engine baseline the P&W RL10A-3-3A.

Pratt & Whitney, in cooperation with the United States Air Force Research Laboratory, established an advanced upper stage expander engine model for the purpose of establishing the individual component requirements necessary to ensure the IHPRPT phase 1 system level goals are achieved. This cycle model was used to establish the performance, cost, weight, and thermodynamic operating requirements of the AEC. The component goals established for the AEC to support the resulting cycle and IHPRPT goals are as follows:

- Increase coolant heat pick-up by 300% with respect to the current state of the art RL10A-3-3A baseline.
- Maintain coolant pressure drop to within 50 psia (3.5 kg/cm**2) with respect to the current state of the art RL10A-3-3A baseline.
- Flight weight target of 65 pounds (29 kg) for the combustion chamber.
- Maintain combustion chamber fabrication costs of the current state of the art RL10A-3-3A baseline.

The AEC design accomplishes these goals. The heat pick-up is increased 300% while simultaneously reducing the required heat exchanger area to approximately 37% of the RL10A-3-3A baseline. Similarly, the heat transfer to normalized pressure drop is increased by a factor of 2.1. Achievement of the above AEC component goals results in a 10% improvement in engine thrust-to-weight and 1% improvement in specific impulse relative to the baseline RL10A-3-3A.

DISCUSSION

The simplicity of the expander-cycle engine offers the ability to lower the cost of placing payloads to orbit. Improving performance of the system through increases in chamber pressure while maintaining the same dimensional envelope is highly desired. Current expander cycle engines are limited in their ability to increase chamber pressure, due to the low heat transfer afforded by the materials used in the combustion chamber. Development of an advanced-technology combustion chamber that increases chamber pressure and provides more performance while maintaining reliability and operability is the key to advancing the ability of the expander engine.

An expander-cycle rocket engine cools the chamber/nozzle components with the engine fuel flow, and the energy picked by the cooling process provides the power to drive the turbopumps. The relatively benign turbine inlet temperature created by this cycle results in weight, cost, and reliability advantages over other cycles (i.e., gas generator, staged combustion). The elimination of combustion devices that drive turbopumps further enhances these advantages. Expander-cycle engines have lower turbopump pressure requirements than staged combustion engines and higher performance potential than gas generator cycles. To reach the true potential of the expander-cycle engine (i.e., highest thrust in the smallest dimensional envelope) the combustion chamber heat pickup must be maximized for maximum power to the drive turbines. Development of the advanced expander-cycle engine depends on this technology issue being resolved through the design, fabrication, and testing of an advanced thrust chamber.

P&W established an advanced expander engine model, which meets the IHPRPT phase 1 system level goals, from which component goals could be determined. The P&W RL10A-3-3A is the baseline for the IHPRPT goals and was used as the starting point for developing the advanced expander engine cycle. The RL10A-3-3A has 16,500 pound (7484 Kg.) vacuum thrust, Specific Impulse of 442.5 seconds, and a thrust lc to weight ratio of 53. It utilizes a two stage turbine driven by the expanded hydrogen from the combustor and nozzle cooling tubes. The RL10 turbine drives both the two stage hydrogen turbopump and, through a gearbox, the single stage Liquid Oxygen (LOX) lc turbopump. The maximum cycle pressure is approximately 1100 PSIA (77.33 Kg/cm2) with a lc chamber pressure of 470 PSIA (33 Kg./cm2). The lc expander cycle developed for the RL10, shown in Figure 1, is used in each member of the RL10 family, covering the 16,500 to 24,750 pound (7484 - 11226 Kg.) thrust range. The advanced expander engine lc cycle, based on the RL10 cycle, established to support the IHPRPT phase 1 goals will allow further growth to 50,000 - 80,000 lbs ~~pounds~~ (22,679 - 36,287 Kg.) while lc maintaining the benefits of the RL10 family history.

The growth potential of the current RL10 family is limited by the fuel pump discharge pressure which is in turn limited by the heat pickup capacity of the combustor and nozzle cooling tubes. While the tubular configuration provides better heat pickup than current milled channel combustor, the moderate conductivity of the RL10 steel tubes limits their heat load capacity per unit area and heat pick up. The ability to transfer more heat across the chamber cooling wall is essential to provide the increased energy required for higher turbopump output, chamber pressure, and thrust, in the advanced expander cycle.

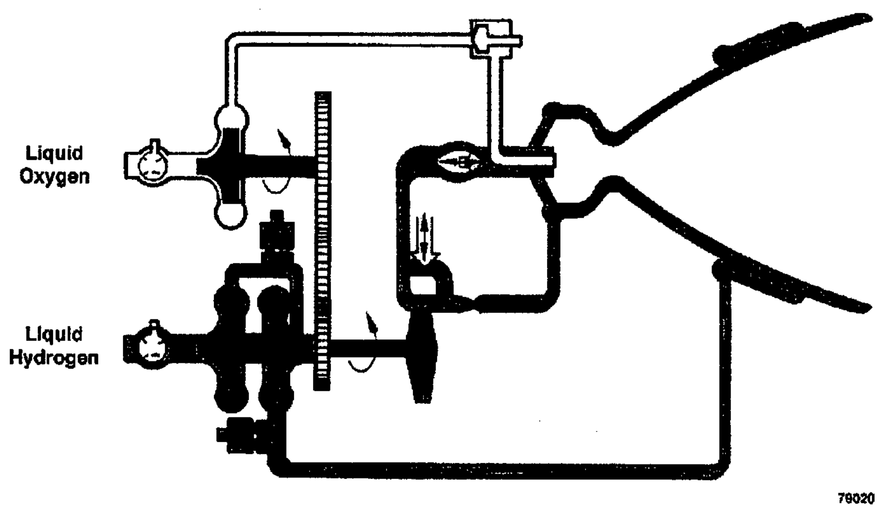

Figure 1 - RL10 Expander Cycle System with Gearbox

Until recently no significant improvement in thermal conductivity was available without an unacceptable sacrifice of material properties such as strength, LCF spell out characteristics, and oxidation/erosion capability. This problem has been solved by the development of PWA 1177 dispersion strengthened copper which provides improved material strength, LCF capability, and conductivity. The Advanced Expander Combustor (AEC) being developed for the AFRL on contract F04611-95-C-0123 uses PWA 1177 to provide the increased heat transfer and resultant energy required to support the advanced expander engine cycle.

The additional heat load capacity provides the required turbine input energy to support an increase in turbopump discharge pressures, allowing an increase in chamber pressure. Analysis of an expander cycle with the improved heat load capacity supports a stable expander cycle ~~operating~~ at a chamber pressure of 1375 PSIA (96.7 Kg./Cm.2) with a ~~maximum~~ cycle lc pressure of 4600 PSIA (323.4 Kg./Cm.2) at the ALH lc fuel turbopump discharge. The ~~final~~ system balance provided a heat load capacity of 22,833 Btu/sec (24M kg/cm² ? N-M/sec) available to drive both the ALH fuel turbopump and the LOX turbopump with at least 5% margin remaining for roll control thrusters, boost pump drive, or equivalent bypass requirements.

The advanced expander engine cycle configured to meet IHPRPT phase 1 goals is shown in figure 2. The predicted advanced expander engine system performance is summarized in Table 1.

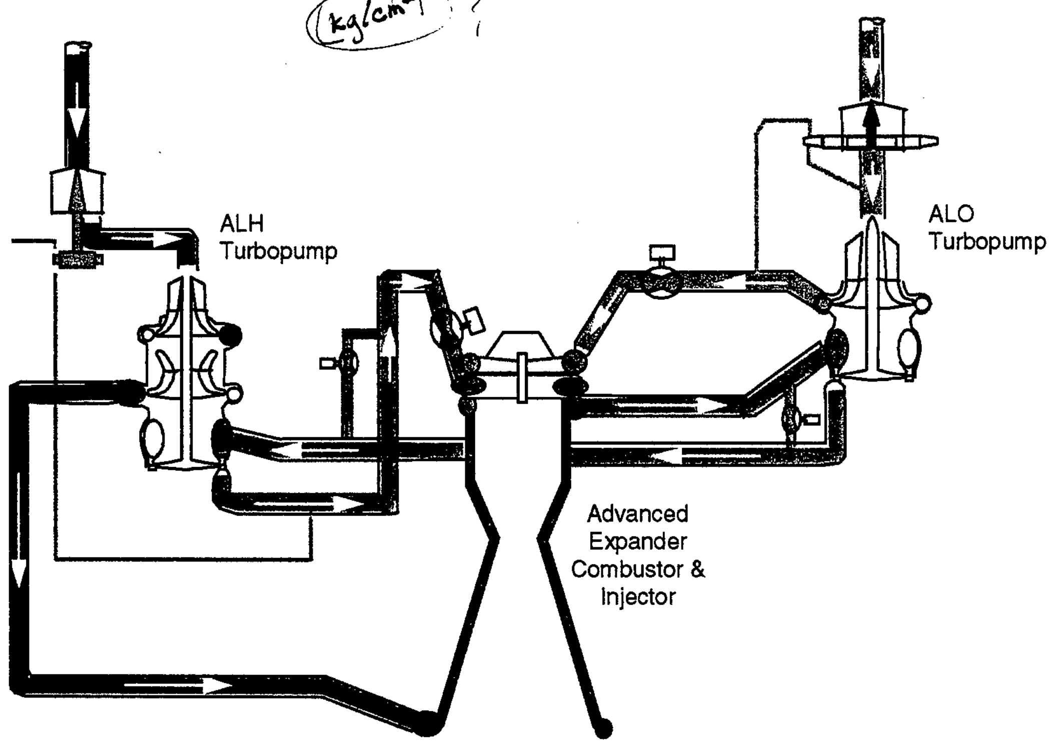

Figure 2. Advanced Expander Engine Cycle Schematic

Table 1. Advanced Expander Engine Cycle Summary

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Vacuum Thrust, lbf	50,334	Chamber Pressure, psia	1375
Engine Mixture Ratio	6.00	Combustion C* Efficiency	0.99
Chamber Mixture Ratio	6.11	Chamber Coolant Q, Btu/s	22,833
Engine Flowrate, lbm/sec	112.0	Chamber Length, in	26.0
Del. Vacuum Isp, sec	450.6	Chamber Contraction Ratio	4.65
Throat Area, in**2	19.09	C*, Char. Velocity, ft/s	7553
Nozzle Efficiency, Cs	0.995	Nozzle AR	64.5
Weight Estimate, lb	715	Nozzle Exit Diameter, in	39.6
Thrust to Weight	70.4	Turbine Bypass, %	5.4

THE ADVANCED EXPANDER COMBUSTOR DESIGN

The AEC design goals are to maximize coolant heat pick-up with a minimum coolant pressure drop and minimum chamber weight and production cost. The accommodation of high heat flux levels requires thermally compliant chamber materials and geometries with high strength liners. The enabling design feature of the AEC is the use of a high strength high conductivity copper alloy, Pratt & Whitney PWA 1177, in a tubular combustor configuration. The AEC has been designed to provide:

- A naturally compliant pressure vessel shape for reduced strain levels in response to thermal stresses.
- Reduced pressure losses of the hydrogen coolant
- Increased surface due to tube crowns allows maximum heat pick-up

The AEC design requirements were distributed to a design team including mechanical, thermal, structural, and fabrication specialists. Establishment of the physical design as well as integration of the individual sub-elements among the various specialists was the responsibility of the mechanical design specialist assigned to lead the team. The AEC is shown in cross section in Figure 4.

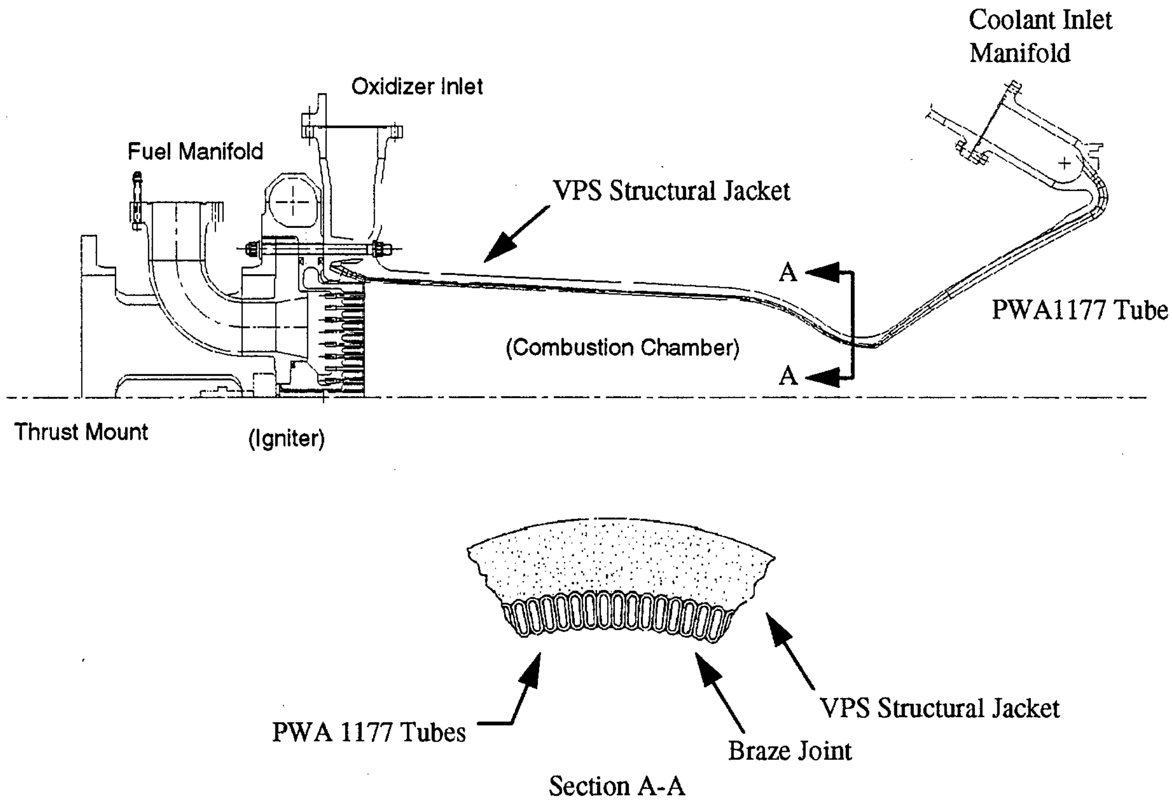

Figure 4. Cross section of the Advanced Expander Combustor

Copper Tubular Liner Design

The challenges of the AEC liner design were to maximize coolant heat pick-up, minimize coolant pressure drop and increase strain range tolerance and ductility, maintain liner material properties throughout the fabrication process, and increase the liner creep strength.

Following a thorough examination of various options in chamber construction, P&W selected a copper-based tubular thrust chamber. The most significant feature is the use of a new copper alloy (PWA 1176) coupled with an improved processing technique (PWA 1177). Using P&W's Rapid Solidification Rate (RSR) powder metallurgy technology, a new, optimized alloy was created that enables the fabrication of high-strength, temperature-resistant copper tubes. In final form, these PWA 1177 tubes can withstand repeated exposure to fabrication temperatures in excess of 1800°F and still retain yield strength five times greater than copper alloys used in current rocket thrust chambers. PWA 1176/1177 is essentially pure copper with a dispersion of fine aluminum oxide particles (alumina, $Al2O3$). The alumina dispersoids allow work hardened strength to be retained, especially at elevated temperatures, without significant loss of thermal conductivity. The result is an advanced high-strength copper alloy that maintains its strength during the manufacturing process.

In addition to the use of this superior copper alloy, the tubular configuration of the chamber provides up to 40 percent more actual surface area (due to the circular tube crowns) — and therefore more heat transfer capability — and lower thermal strain (increased life) than smooth wall hot-side fabricated channel configurations. The tubular construction also provides improved pressure drop characteristics over rectangular channel designs.

A P&W-developed braze process is used to braze the tube to each other and to the coolant manifold rings. The manifolds are left open during brazing and welded closed after subsequent machining of the tube ends inside the manifolds. This allows the coolant system integrity to be easily inspected prior to welding the manifolds closed. At this point the VPS jacket is applied to the outside of the tube bundle to provide structural support during subsequent fabrication processing. The assembled tube bundle of the AEC prior to braze is shown below in Figure 5.

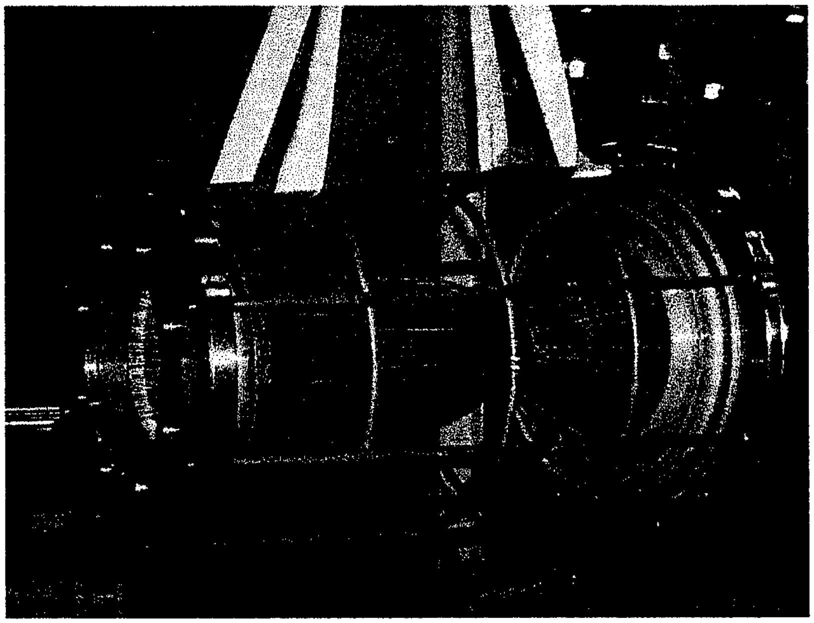

Figure 5 – Assembled Copper Tube bundle Prior to Braze

The three primary requirements for a successful brazing process are to control the diffusion of braze into the tubes, minimize the braze fillet, and ensure sealing of the tubes to the manifolds. A copper-based braze alloy was chosen for joining PWA 1177 because it has melt-point compatibility with the tube alloy, good thermal conductivity, and a lower diffusion potential for interaction with the tubes than other brazes. In addition, this braze material provides hydrogen compatibility so it will not react with hydrogen during brazing or operation. Figure 7 shows a typical tube-to-tube braze joint.

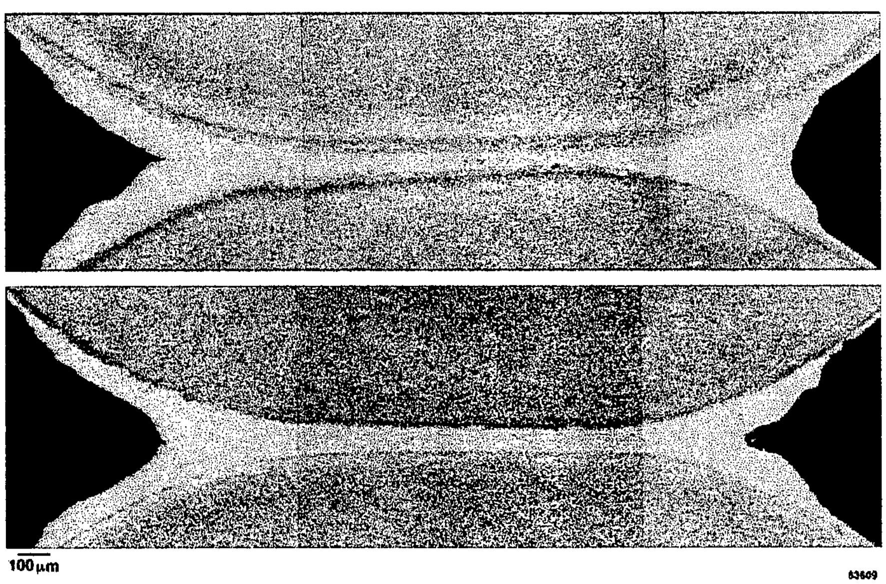

Figure 6. Typical PWA 1177 Tube-to-Tube Braze Joint; A Small Braze Fillet and Minimal Braze Tube Reaction Will Maximize Tube Chamber Performance and Maintain Structural Integrity

Structural Jacket Design

The challenges of the AEC structural jacket design were to provide thermal compatibility with the chamber liner, accommodation of hoop and axial loads, allow low cost manufacturing approaches, and provide high specific yield strength and ductility for low weight.

The structural jacket was applied by a quick and inexpensive method called vacuum plasma spray (VPS). The VPS system uses a high-velocity plasma-heated stream of molten metal particles in a near vacuum atmosphere to deposit a strongly adherent, highly dense structural jacket of an alloy such as AISI 347 stainless steel. The steel, when heat treated, exhibits properties comparable to wrought alloys. The VPS process was carried out in a large vacuum chamber that incorporated a high-power plasma spray gun assembly manipulated by a robot. The robot was programmed to manipulate the gun assembly over the copper tubular rocket thrust chamber during the plasma spray operation. Another robot manipulated and rotated the thrust chamber under the plasma spray plume.

The VPS jacket construction method was originally selected to avoid time-consuming, costly electroforming of the chamber jackets over PWA 1177 tube bundles. The potential advantage of the VPS jacket approach is that uniform, wrought-equivalent material may be quickly and efficiently applied to the hot-wall PWA 1177 tubes, without intermediate detail component fabrication. This results in a high-strength, near-net-shape, integral chamber jacket assembly. The VPS jacket complements the tubular chamber construction by eliminating the majority of welding operations currently required on many state-of-the-art, operational thrust chambers. The VPS process can be used to build up the jacket locally where bosses or other attaching features are required.

The AEC is shown below after the application of the 347SS VPS structural jacket prior to heat treat is shown below in Figure 7.

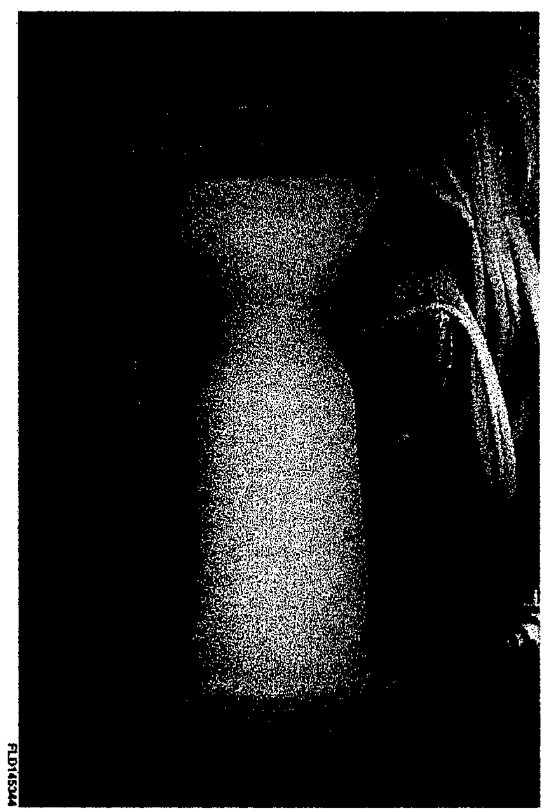

Figure 7. AEC With VPS Structural Jacket Applied

Although the AEC uses AISI 347 steel, the VPS techniques used to apply and process the jacket are applicable to other, higher strength alloys. Structural analyses carried out as part of P&W's IR&D program indicate that the characteristics of the jacket alloy have negligible effect on tube life. Future flight systems will thus be able to employ high-specific strength alloys for light weight. Pratt & Whitney continues to investigate other alloys for VPS application.

Structural and Life Assessment

The combination of very high thermal gradients and pressures leads to multiaxial straining of the liner hot wall, which produces inelastic stress-strain material response. Full-scale and subscale testing of conventional milled channel combustors identified cyclically progressive midchannel wall thinning and bulging, with subsequent rupture of the coolant passage. This experience confirms the high degree of inelastic deformation the liner hot wall undergoes.

To improve the durability of the liner, the level of cyclic strain must be controlled. The AEC uses tubular coolant passages to enhance cyclic life compared to the conventional, less durable, milled channel liner configuration. The AEC uses oxide dispersion strengthened PWA for improved strength as well as high conductivity. This PWA 1177 tubular configuration provides the following advantages:

- Preferable pressure vessel shape (round versus square) for supporting the pressure differential between the coolant and combustion gas.
- A more thermally compliant structure in the hoop direction (flexible curved wall as opposed to a stiff flat wall).
- Improved high-temperature tensile strength, dwell LCF, and creep resistance
- Maximized fatigue life through reduced cyclic strain range and reduced level of biaxial strain.

Structural analyses, conducted in support of a P&W IR&D program, predicted that the combined effect of PWA 1177 material and a tubular configuration offers a durable liner design. Figure 8 shows effective stress-strain hysteresis loops predicted for the liner hot wall for two simulated engine firings.

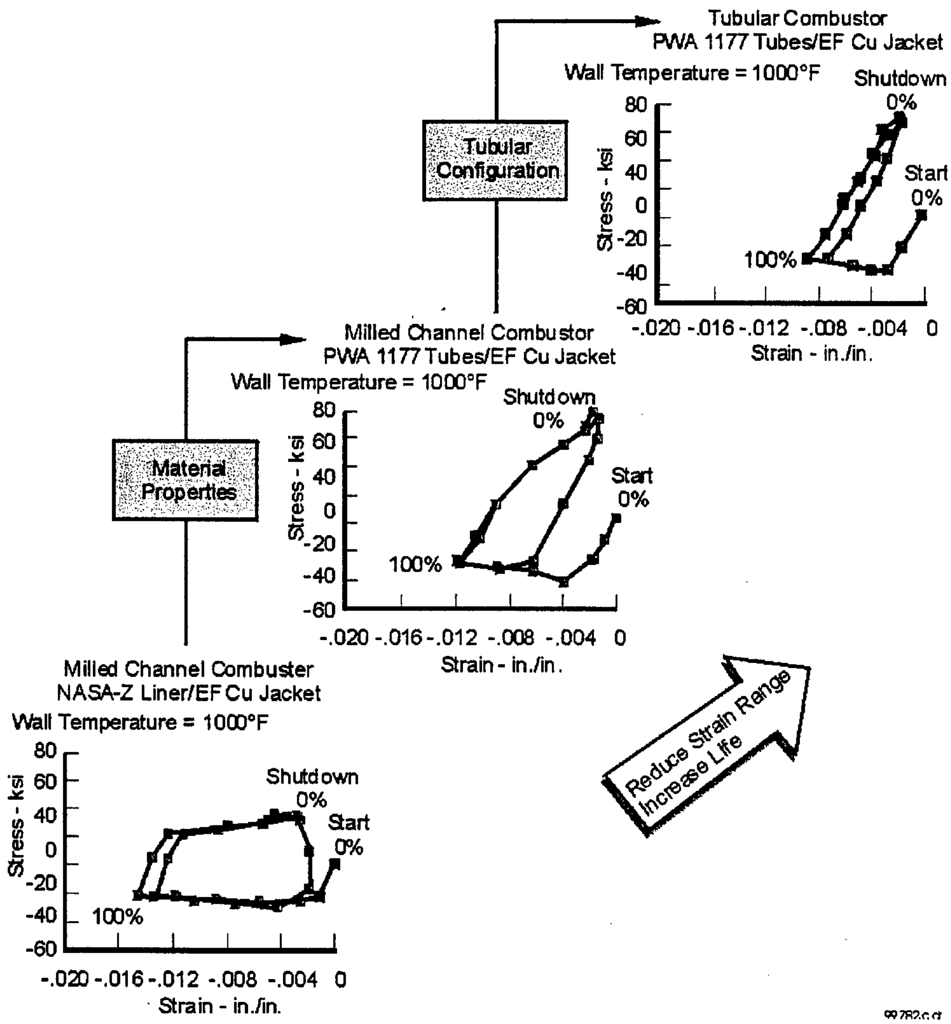

Figure 8. Increased Chamber Life Results From High Strength Copper Alloy and Tubular Configuration.

The width of the loop is related to the amount of inelastic strain the local hot-wall material undergoes. Generally speaking, the wider the area, the more the inelastic damage, and the lower the fatigue life. This study first focused on the material effect for a milled channel configuration (NASA-Z Milled lower left in Figure 8) and PWA 1177 Milled [center]). For identical temperatures and pressures, the higher yield strength of the PWA 1177 resulted in less inelastic strain than that of the NASA-Z liner. Next, the effect of configuration only was studied. A PWA 1177 milled channel was compared to a PWA 1177 tubular passage (upper right in Figure 8). Here the compliant shape of the tube wall led to even more reduced inelastic straining of the liner wall, as evident in the tightening of the hysteresis loop. This study shows that a major reduction in cyclic strain range can be achieved by using a PWA 1177 tubular liner in place of the conventional NASA-Z milled channel design. Based on the analysis results, a simple fatigue life comparison can be made using the method of universal slopes shown in Figure 9. Based on this, a PWA 1177 tubular liner can have 2.5 times the fatigue life of a conventional milled chamber. This results in a robust, durable design that can be tested numerous times with much lower risk of liner hot-wall failures, which have been common to milled chamber designs.

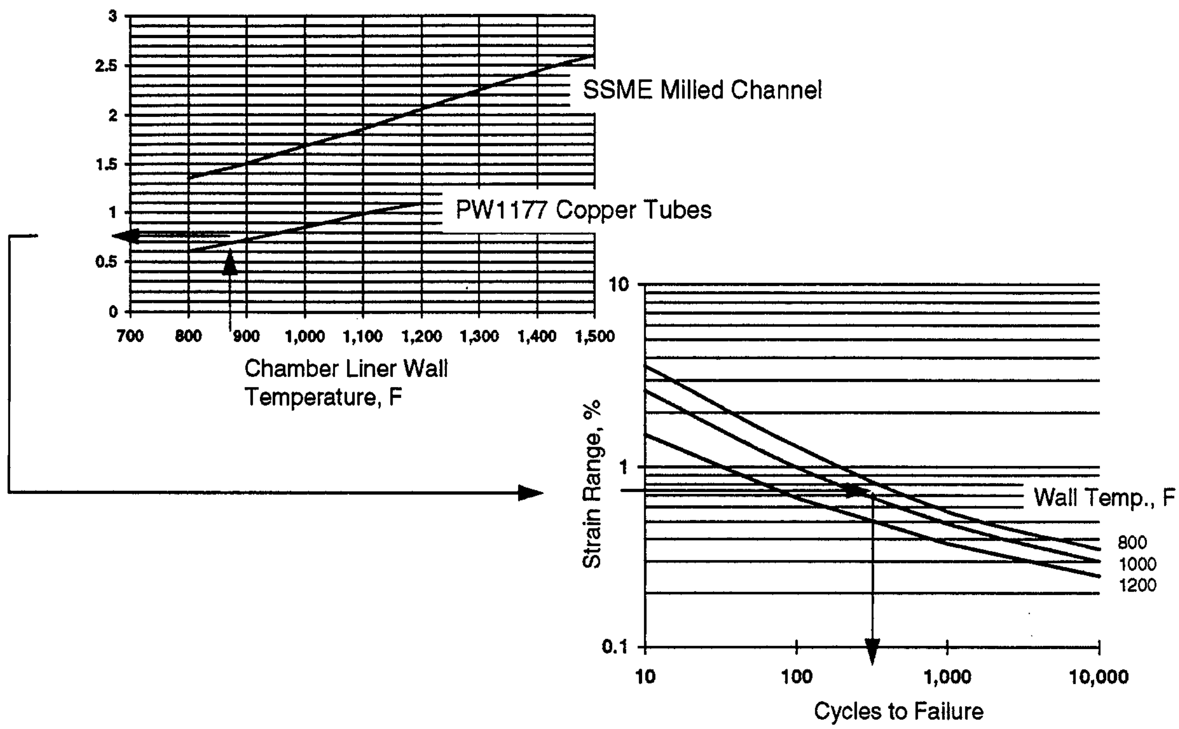

Figure 9. AEC Copper Tubular Configuration Has Increased Fatigue Life.

Injector Design

P&W has designed and fabricated an advanced injector compatible with the AEC, which may be used during testing of the AEC. This injector was designed for high combustion efficiency with minimal circumferential wall heat flux and mixture ratio variations. Tangential swirl elements were selected to provide a high degree of gaseous fuel and liquid oxidizer atomization, vaporization, and mixing. A torch ignitor design was selected for high performance and simplicity.

SUMMARY AND CONCLUSION

The AEC is on schedule for testing at Pratt & Whitney's Florida test facilities in mid-year 1999. The design has been completed and the hardware fabrication is nearing completion. The AEC test requirements are being integrated with the Air Force Research Laboratory in parallel with fabrication to ensure the facility is ready to support testing of the AEC on schedule.

Pratt & Whitney's Advanced Expander Combustor integrates state-of-the-art materials, a high performance thrust chamber geometric configuration, and advanced fabrication approaches into a thrust chamber unit that supports the IHPRPT phase 1 goals.